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## Description

### METHOD FOR FABRICATING SEMICONDUCTOR DEVICE

#### Technical Field

5       The present invention relates to a method for epitaxially growing a semiconductor-metal compound layer, in particular, a semiconductor-metal compound layer with high crystal orientation, in a surface portion of a semiconductor layer.

10

#### Background Art

15       In a semiconductor integrated circuit device required to be operated at a high speed, in accordance with recent refinement of semiconductor devices, increase in the sheet resistance and the contact resistance of a semiconductor layer including an impurity dispersed therein has become a serious problem.

20       As one means for overcoming this problem, a process for forming a silicide layer in a surface portion of the semiconductor layer has been proposed. A variety of metals have been proposed to be used for forming the silicide layer, among which a cobalt disilicide ( $\text{CoSi}_2$ ) layer formed by using cobalt is regarded as a particularly promising silicide layer because it is good in both thermal stability and specific  
25       resistance.

In the case where a surface portion of a silicon substrate is silicided by using cobalt, however, agglomeration can be caused in the cobalt silicide layer or a spike defect can be caused in the cobalt silicide layer during a reaction process occurring between cobalt atoms and silicon atoms (IEDM 1995-449, K. Goto). The agglomeration of the cobalt silicide layer leads to open circuit failure, and the occurrence of a spike defect leads to junction leakage.

As means for preventing the agglomeration and the occurrence of a spike defect in the cobalt silicide layer, a method for forming a cobalt silicide layer by epitaxial growth as follows is proposed in an article (Appl. Phys. Lett. 68, 1996, June). Specifically, the article proposes a technique of epitaxial growth of a cobalt silicide layer (oxide mediated epitaxy; OME) by forming a  $\text{SiO}_x$  ( $x < 2$ ) film with a thickness of 0.5 through 1.5 nm on a semiconductor layer of silicon crystal, depositing a cobalt film in approximately several nm on the  $\text{SiO}_x$  film under ultra high vacuum and carrying out annealing for causing a reaction between cobalt atoms and silicon atoms. It is also described that the  $\text{SiO}_x$  film plays a role for promoting the growth of the cobalt silicide layer.

However, the aforementioned method for forming a cobalt silicide layer by the epitaxial growth requires ultra-high vacuum equipment for the deposition of a cobalt film, and the

ultra-high vacuum equipment is not employed in a general process for semiconductors of silicon. Therefore, this method is not suitable to the mass production process.

Furthermore, since the cobalt film is formed on the  $\text{SiO}_x$  ( $x < 2$ ) film having a very small thickness and including silicon excessively as compared with a stoichiometric composition, various problems occur in the aforementioned method due to variation in the film quality and the thickness of the  $\text{SiO}_x$  film. Specifically, in the case where a pin hole is formed in the  $\text{SiO}_x$  film, cobalt and silicon are explosively reacted to each other through the pin hole, and hence, there arises a problem that the cobalt silicide layer cannot be epitaxially grown; and in the case where the thickness of the  $\text{SiO}_x$  film is fluctuated, the reaction between the cobalt atoms and the silicon atoms is too rapidly proceeded in a portion with a small thickness, and hence, there arises a problem that the cobalt silicide layer cannot be satisfactorily epitaxially grown.

#### Disclosure of the Invention

In consideration of the aforementioned problems, an object of the invention is stably epitaxially growing a semiconductor-metal compound layer, such as a cobalt silicide layer, free from agglomeration and a spike defect under a vacuum region or by using a fabrication system generally

employed in the semiconductor mass-production process.

In order to achieve the object, the present inventors have variously examined the causes of the agglomeration and a spike defect occurring in a cobalt silicide layer formed by the epitaxial growth, resulting in finding the following: Thermodynamically, the mechanism for forming cobalt silicide through a reaction between cobalt atoms and silicon atoms is brought by proceeding a reaction,  $\text{Co}_2\text{Si} \rightarrow \text{CoSi} \rightarrow \text{CoSi}_2$ . In the reaction path of  $\text{Co}_2\text{Si} \rightarrow \text{CoSi} \rightarrow \text{CoSi}_2$ , however, the interface energy is so unstable and ununiform that cobalt silicide is polycrystallized, resulting in causing agglomeration and a spike defect.

Accordingly, the present inventors have concluded that  $\text{CoSi}_2$  can be formed without passing through the reaction path of  $\text{Co}_2\text{Si} \rightarrow \text{CoSi} \rightarrow \text{CoSi}_2$  by epitaxially growing the cobalt silicide layer after forming a seed layer of  $\text{CoSi}_2$  on the interface between a semiconductor layer including silicon and a cobalt film.

Therefore, a variety of examination has been made on a method for forming a seed layer of  $\text{CoSi}_2$  on the interface between the semiconductor layer including silicon and the cobalt film. As a result, it has been found that a seed layer of  $\text{CoSi}_2$  can be formed by controlling the concentration of oxygen atoms present between the semiconductor layer and the cobalt film. Specifically, when a cobalt film is

deposited on a semiconductor layer including oxygen atoms distributed in a region in the vicinity of the surface, the amount of oxygen atoms sandwiched between the semiconductor layer and the cobalt film is decreased as compared with the  
5 case where a  $\text{SiO}_x$  film is sandwiched between the semiconductor layer and the cobalt film. Therefore, the seed layer of  $\text{CoSi}_2$  can be formed between the semiconductor layer and the cobalt film.

TELETYPE  
10 The present invention was devised on the basis of these findings, and specifically, the first method for fabricating a semiconductor device of this invention comprises the steps of distributing a nonmetal element in a region in the vicinity of a surface portion of a semiconductor layer; depositing a metal film on the semiconductor layer; and  
15 epitaxially growing a semiconductor-metal compound layer in the surface portion of the semiconductor layer by causing a reaction between an element included in the semiconductor layer and a metal included in the metal film through annealing carried out on the metal film.

20 In the first method for fabricating a semiconductor device of this invention, the metal film is deposited on the semiconductor layer after distributing the nonmetal element in the region in the vicinity of the surface portion of the semiconductor layer, and thereafter, the reaction between the  
25 element included in the semiconductor layer and the metal

included in the metal film is caused by carrying out the annealing on the metal film. Therefore, the metal included in the metal film and the element included in the semiconductor layer can be avoided from too rapidly reacting with each other, so as to prevent polycrystallization of the semiconductor-metal compound layer. Thus, according to the invention, a semiconductor-metal compound layer free from agglomeration and a spike defect can be stably formed under vacuum generally employed in the semiconductor mass production process and at a low temperature.

In the first method for fabricating a semiconductor device, the step of distributing the nonmetal element preferably includes the steps of forming a compound layer including a semiconductor element and the nonmetal element on the semiconductor layer; distributing the nonmetal element included in the compound layer in the region in the vicinity of the surface portion of the semiconductor layer through recoil by irradiating the compound layer with a particle energy beam; and removing the compound layer.

In this manner, the nonmetal element included in the compound layer can be definitely distributed in the region in the vicinity of the surface portion of the semiconductor layer through the recoil caused by the irradiation with the particle energy beam.

In the first method for fabricating a semiconductor

device, the step of distributing the nonmetal element preferably includes the steps of forming a compound layer including a semiconductor element and the nonmetal element on the semiconductor layer; and distributing the nonmetal  
5 element included in the compound layer in the region in the vicinity of the surface portion of the semiconductor layer through recoil and removing the compound layer by irradiating the compound layer with a particle energy beam.

In this manner, the nonmetal element included in the  
10 compound layer can not only be definitely distributed in the region in the vicinity of the surface portion of the semiconductor layer through the recoil caused by the irradiation with the particle energy beam, but also there is no need to conduct the step of removing the compound layer.

15 In these cases, a semiconductor layer having a face-centered cubic crystal structure, a semiconductor-metal compound layer having a face-centered cubic crystal structure and an amorphous compound layer can be used.

Also in these cases, the particle energy beam  
20 preferably includes a nonmetal element.

In this manner, the element included in the particle energy beam can be prevented from harmfully affecting the semiconductor layer.

In the first method for fabricating a semiconductor  
25 device, a semiconductor layer having a face-centered cubic

crystal structure and a semiconductor-metal compound layer having a face-centered cubic crystal structure can be used.

In the first method for fabricating a semiconductor device, a semiconductor layer having a diamond or zinc blende  
5 crystal structure and a semiconductor-metal compound layer having a calcium fluoride crystal structure can be used.

Preferably, in the first method for fabricating a semiconductor device, the semiconductor layer is a silicon layer, the nonmetal element is oxygen, the metal film is a  
10 cobalt film, and the semiconductor-metal compound layer is a cobalt silicide layer.

In this manner, a cobalt silicide layer that is thermally stable and has low sheet resistance can be definitely epitaxially grown in the surface portion of the  
15 semiconductor layer.

In this case, the oxygen preferably has a concentration of  $4 \times 10^{14}$  through  $4 \times 10^{15} \text{ cm}^{-2}$ .

In this manner, the reaction between cobalt atoms and silicon atoms can be satisfactorily proceeded, so that a  
20 cobalt silicide layer can be satisfactorily epitaxially grown in the surface portion of the silicon layer.

Also in this case, the step of distributing the nonmetal element preferably includes a step of forming a silicon oxide film on the silicon layer and distributing  
25 oxygen included in the silicon oxide film in the region in



the vicinity of the surface portion of the silicon layer by irradiating the silicon oxide film with the particle energy beam.

In this manner, oxygen atoms can be definitely distributed in the region in the vicinity of the surface portion of the silicon layer.

The second method for fabricating a semiconductor device of this invention comprises the steps of forming a gate electrode on a semiconductor layer; forming impurity layers on both sides of the gate electrode in the semiconductor layer; distributing a nonmetal element in a region in the vicinity of a surface portion of the semiconductor layer; depositing a metal film on the semiconductor layer; and epitaxially growing a semiconductor-metal compound layer in the surface portion of the semiconductor layer by causing a reaction between an element included in the semiconductor layer and a metal included in the metal film through annealing carried out on the metal film.

In the second method for fabricating a semiconductor device of this invention, a cobalt silicide layer that is thermally stable and has low sheet resistance and contact resistance can be formed in a surface portion of the semiconductor layer serving as a source or drain region, and a silicide layer with good quality can be formed in a surface

portion of the gate electrode. As a result, the performance of a semiconductor integrated circuit device including the MOSFET can be improved without increasing the number of fabrication procedures.

5 In the second method for fabricating a semiconductor device, the step of distributing the nonmetal element preferably includes the steps of forming a compound layer including a semiconductor element and the nonmetal element on the semiconductor layer; distributing the nonmetal element  
10 included in the compound layer in the region in the vicinity of the surface portion of the semiconductor layer through recoil by irradiating the compound layer with a particle energy beam; and removing the compound layer.

In this manner, the nonmetal element included in the  
15 compound layer can be definitely distributed in the region in the vicinity of the surface portion of the semiconductor layer through the recoil caused by the irradiation with the particle energy beam.

Preferably, in the second method for fabricating a  
20 semiconductor device, the semiconductor layer is a silicon layer, the nonmetal element is oxygen, the metal film is a cobalt film, and the semiconductor-metal compound layer is a cobalt silicide layer.

In this manner, a cobalt silicide layer that is  
25 thermally stable and has low sheet resistance can be

definitely epitaxially grown in the surface portion of the semiconductor layer.

In this case, the oxygen preferably has a concentration of  $4 \times 10^{14}$  through  $4 \times 10^{15} \text{ cm}^{-2}$ .

5 In this manner, the reaction between cobalt atoms and silicon atoms can be satisfactorily proceeded, so that the cobalt silicide layer can be satisfactorily epitaxially grown in the surface portion of the silicon layer.

#### 10 Brief Description of Drawings

FIG. 1(a) is a diagram for showing the plane structure of a semiconductor device according to Embodiment 1.

FIG. 1(b) is a cross-sectional view taken on line Ib-Ib of FIG. 1(a).

15 FIGS. 2(a) through 2(c) are cross-sectional views for showing procedures in a method for fabricating a semiconductor device according to Embodiment 2.

FIGS. 3(a) through 3(c) are cross-sectional views for showing other procedures in the method for fabricating a  
20 semiconductor device according to Embodiment 2.

FIGS. 4(a) and 4(b) are cross-sectional views for showing still other procedures in the method for fabricating a semiconductor device according to Embodiment 2.

FIGS. 5(a) through 5(c) are cross-sectional views for  
25 showing procedures in a method for fabricating a

semiconductor device according to Embodiment 3.

FIGS. 6(a) through 6(c) are cross-sectional views for showing other procedures in the method for fabricating a semiconductor device according to Embodiment 3.

5        FIGS. 7(a) and 7(b) are cross-sectional views for showing still other procedures in the method for fabricating a semiconductor device according to Embodiment 3.

10        FIG. 8 is a characteristic diagram for showing the relationship between an oxygen concentration and the degree of epitaxial growth obtained by measuring the concentration of oxygen atoms by low energy SIMS.

#### **Best Mode for Carrying Out the Invention**

##### **EMBODIMENT 1**

15        A semiconductor device according to Embodiment 1 of the invention will now be described with reference to FIGS. 1(a) and 1(b).

20        FIG. 1(a) shows the plane structure of the semiconductor device of Embodiment 1 and FIG. 1(b) shows the cross-sectional structure taken on line Ib-Ib of FIG. 1(a).

The semiconductor device of Embodiment 1 may be any type of transistors including a CMOS transistor, a pMOS transistor and an nMOS transistor, and is herein described as an n-type MOS transistor.

25        As is shown in FIGS. 1(a) and 1(b), an n-type channel

stopper 11 is formed in a surface portion of a semiconductor substrate 10 of n-type silicon crystal having specific resistance of several  $\Omega \cdot \text{cm}$ , a field insulating film 13 serving as an isolation region is formed on the channel stopper 11, and a p-type well region 12 is formed in a portion of the semiconductor substrate 10 surrounded with the channel stopper 11.

In portions to be used as source and drain regions in the p-type well region 12, n-type low concentration impurity diffusion layers 16 and n-type high concentration impurity diffusion layers 18 having the LDD structure are formed. Also, on a portion of the semiconductor substrate 10 sandwiched between the source region and the drain region, a gate electrode 15 of a polysilicon film is formed with a gate insulating film 14 of a silicon oxide film sandwiched therebetween, and a sidewall 17 of a silicon oxide film is formed on the side face of the gate electrode 15.

As a characteristic of Embodiment 1, an epitaxially grown layer of cobalt disilicide ( $\text{CoSi}_2$ ) is formed in a surface portion of the n-type high concentration impurity diffusion layer 18, and a polycrystalline cobalt disilicide layer is formed in a surface portion of the gate electrode 15 under conditions the same as those for growing the epitaxially grown layer on the n-type high concentration impurity diffusion layer 18 so as to have an epitaxial

relationship with each crystal grain of the polysilicon. The silicide layers formed in the surface portions of the n-type high concentration impurity diffusion layer 18 and the gate electrode 15 have a thickness of, for example, approximately 30 through 50 nm. Therefore, the resistance values of the n-type high concentration impurity diffusion layer 18 and the gate electrode 15 can be sufficiently lowered so as to improve the performance of a semiconductor integrated circuit device including the MOSFET of Embodiment 1.

An interlayer insulating film 22 is deposited on the semiconductor substrate 10, a metal interconnect 24 of, for example, an aluminum alloy film is formed on the interlayer insulating film 22, and the metal interconnect 24 is covered with a protection insulating film 25. The metal interconnect 24 is connected to the epitaxial silicide layer 21 formed in the surface portion of the n-type high concentration impurity diffusion layer 18 through a contact hole 23 formed in the interlayer insulating film 22. Therefore, the contact resistances of the n-type high concentration impurity diffusion layer 18 and the metal interconnect 24 can be sufficiently lowered.

#### EMBODIMENT 2

A method for fabricating the semiconductor device of Embodiment 1 will now be described as Embodiment 2 of the invention with reference to FIGS. 2(a) through 2(c), 3(a)

through 3(c), 4(a) and 4(b).

First, after forming a silicon oxide film with a small thickness on a semiconductor substrate 100 of n-type silicon crystal shown in FIG. 2(a), a silicon nitride film is deposited on the silicon oxide film. Thereafter, the silicon nitride film is patterned by the known photolithography technique and etching technique, so as to remove a portion of the silicon nitride film corresponding to a field insulating film region.

Next, with the patterned silicon nitride film used as a mask, an n-type impurity such as phosphorus and arsenic is ion implanted into the semiconductor substrate 100 at a high concentration, so as to form a channel stopper 101, and then, a p-type impurity such as boron is ion implanted into the semiconductor substrate 100, so as to form a p-type well region 102. Thereafter, the semiconductor substrate 100 is subjected to LOCOS for oxidizing a surface portion of the semiconductor substrate 100 not covered with the silicon nitride film through annealing, so as to form a field insulating film 103 with a thickness of, for example, 400 nm in the surface portion of the semiconductor substrate 100. The channel stopper 101 and the p-type well region 102 are activated through this annealing. Then, the silicon oxide film and the silicon nitride film are removed.

Next, a gate insulating film 104 of a silicon oxide

film with a thickness of, for example, 5 through 10 nm is formed on the entire surface of the semiconductor substrate 100 by, for example, thermal oxidation, a polysilicon film is deposited on the gate insulating film 104 by, for example, CVD, and the polysilicon film is patterned by the known photolithography technique and etching technique into a gate electrode 105.

Then, with the gate electrode 105 used as a mask, an n-type impurity such as arsenic and phosphorus is ion implanted into the semiconductor substrate 100 at a low concentration, so as to form an n-type low concentration impurity layer 106 as is shown in FIG. 2(b).

Subsequently, a silicon oxide film is deposited on the entire surface of the semiconductor substrate 100, and the silicon oxide film is subjected to anisotropic etching, so as to form a sidewall 107 on the side face of the gate electrode 105 as is shown in FIG. 2(c). Thereafter, with the gate electrode 105 and the sidewall 107 used as masks, an n-type impurity such as arsenic and phosphorus is ion implanted into the semiconductor substrate 100 at a high concentration, so as to form an n-type high concentration impurity layer 108. Then, the semiconductor substrate 100 is subjected to annealing, so as to active the n-type low concentration impurity layer 106 and the n-type high concentration impurity layer 108.



The sidewall 107 may be formed from a silicon nitride film instead of the silicon oxide film. Also, the annealing for activation may be carried out in first and second rapid thermal annealing processes described below.

5        Next, as is shown in FIG. 3(a), nonmetal element ions such as oxygen ions are ion implanted into the semiconductor substrate 100 at low acceleration energy of, for example, 100 through 500 eV, so that an oxygen atom distributed region 109 where oxygen atoms are distributed in a direction along the  
10        substrate surface can be formed in the vicinity of the surface of the n-type high concentration impurity layer 108 and in the vicinity of the surface of the gate electrode 105 as is shown in FIG. 3(b). The oxygen atom distributed region 109 may be formed by, instead of the ion implantation of the  
15        oxygen ions, plasma doping for distributing oxygen atoms.

The depth for distributing the oxygen atoms of the oxygen atom distributed region 109 is preferably 0.5 through 5 nm from the surface of the n-type high concentration impurity layer 108 or the gate electrode 105, and the  
20        concentration of the oxygen atoms included in the oxygen atom distributed region 109 is preferably  $4 \times 10^{14} \text{ cm}^{-2}$  through  $4 \times 10^{15} \text{ cm}^{-2}$ . The reasons will be described later.

125 A, >        Next, sputtering is carried out in a sputtering system having a chamber kept at a vacuum of  $1 \times 10^5$  through  $1 \times 10^7$   
25        Pa, so as to deposit a metal film, such as a cobalt film 110,

on the entire surface of the semiconductor substrate 100 as is shown in FIG. 3(c).

The oxygen atom distributed region 109 is formed between the cobalt film 110 and the n-type high concentration impurity layer 108 or the gate electrode 105, and the oxygen atoms are distributed in a depth of 0.5 through 5 nm from the surface of the n-type high concentration impurity layer 108 or the gate electrode 105. Therefore, cobalt atoms included in the cobalt film 110 are prevented from diffusing into the semiconductor substrate 100 by the oxygen atom distributed region 109. Also, the crystal lattice of silicon present below the oxygen atom distributed region 109 can be seen from the cobalt atoms included in the cobalt film 110, and hence, even when a region above the oxygen atom distributed region 109 is disturbed by the ion implantation or the plasma doping, the reaction of the cobalt atoms is affected by the crystal structure of a region below the oxygen atom distributed region 109 of the semiconductor substrate 100. Therefore, a nucleus (not shown) of cobalt disilicide ( $\text{CoSi}_2$ ) having a lattice constant matching to that of silicon crystal is formed on the interface between the n-type high concentration impurity layer 108 and the cobalt film 110. Furthermore, the gate electrode 105 is formed from polysilicon, and hence, a nucleus of cobalt disilicide ( $\text{CoSi}_2$ ) is formed with respect to each crystal grain of the polysilicon in the same manner

as in the reaction between the cobalt atoms and the silicon atoms in the n-type high concentration impurity layer 108.

Next, the first rapid thermal annealing (RTA) is carried out for keeping the semiconductor substrate 100 at a temperature of 500°C for 10 seconds. Thus, the cobalt atoms included in the cobalt film 110 are diffused into the silicon region through the nucleus of cobalt disilicide and react with the silicon atoms. Therefore, as is shown in FIG. 3(c), an epitaxially grown layer (hereinafter referred to as a first epitaxial silicide layer) 111A of cobalt disilicide ( $\text{CoSi}_2$ ) corresponding to the crystal structure of the previously formed nucleus of cobalt disilicide is formed in surface portions of the n-type high concentration impurity layer 108 and the gate electrode 105.

In the case where the cobalt film 110 has a thickness of 5 nm, the first epitaxial silicide layer 111A has a thickness of approximately 17 through 18 nm, and in the case where the cobalt film 110 has a thickness of 10 nm, the first epitaxial silicide layer 111A has a thickness of approximately 34 through 36 nm.

Furthermore, in the case where the semiconductor substrate 100 has a face-centered cubic crystal structure, the first epitaxial silicide layer 111A also has a face-centered cubic crystal structure, and in the case where the semiconductor substrate 100 has a diamond or zinc blende

crystal structure, the first epitaxial silicide layer 111A has a calcium fluoride (fluorite) crystal structure.

As described above, the oxygen atom distributed region 109 is formed in the regions at the depth of 0.5 through 5 nm from the surface in the vicinity of the surfaces of the n-type high concentration impurity layer 108 and the gate electrode 105, and hence, the cobalt atoms included in the cobalt film 110 are not directly in contact with the silicon atoms included in the n-type high concentration impurity layer 108 or the gate electrode 105. Therefore, the cobalt atoms and the silicon atoms are not reacted with each other too rapidly, so that agglomeration and polycrystallization of the first epitaxial silicide layer 111A can be avoided.

In the case where the concentration of the oxygen atoms included in the oxygen atom distributed region 109 is lower than  $4 \times 10^{14} \text{ cm}^{-2}$ , the cobalt atoms and the silicon atoms are too rapidly reacted with each other, so that there can be a fear of the agglomeration or the polycrystallization of the first epitaxial silicide layer 111A. On the other hand, in the case where the concentration of the oxygen atoms is higher than  $4 \times 10^{15} \text{ cm}^{-2}$ , a distance between the cobalt atoms and the crystal lattice of the semiconductor substrate 100 becomes too large to satisfactorily cause the reaction between the cobalt atoms and the silicon atoms. Accordingly, the concentration of the oxygen atoms included in the oxygen

atom distributed region 109 is preferably  $4 \times 10^{14} \text{ cm}^{-2}$  through  $4 \times 10^{15} \text{ cm}^{-2}$ .

In the first epitaxial silicide layer 111A, all layers may be formed from cobalt disilicide ( $\text{CoSi}_2$ ), or the lowermost layer (closer to the silicon layer) may be formed from cobalt disilicide ( $\text{CoSi}_2$ ) with the uppermost layer (closer to the cobalt film 110) formed from cobalt silicide ( $\text{CoSi}$ ). In the first epitaxial silicide layer 111A of Embodiment 2, the lowermost layer is formed from cobalt disilicide and the uppermost layer is formed from cobalt silicide. When a cobalt disilicide layer is formed at least on the interface with the silicon layer, the agglomeration of the cobalt silicide layer can be avoided, resulting in reducing a leakage current.

Next, as is shown in FIG. 4(a), a portion of the cobalt film 110 not reacted in the first rapid thermal annealing is removed by using an etchant of, for example, a mixture of an ammonia solution and hydrogen peroxide or a mixed acid solution including hydrochloric acid. Thereafter, the second rapid thermal annealing (RTA) is carried out for keeping the semiconductor substrate 100 at a temperature of  $800^\circ\text{C}$  for 10 seconds. Thus, the cobalt silicide included in the uppermost layer of the first epitaxial silicide layer 111A is also grown to cobalt disilicide, and hence, the first epitaxial silicide layer 111A is changed into a second epitaxial

silicide layer 111B in which all layers are formed from cobalt disilicide.

In the case where all the layers of the first epitaxial silicide layer 111A are formed from cobalt disilicide ( $\text{CoSi}_2$ ),  
5 the second rapid thermal annealing can be omitted. In this case, the second epitaxial silicide layer 111B mentioned in the following description is read as the first epitaxial silicide layer 111A.

Next, as is shown in FIG. 4(b), an interlayer  
10 insulating film 112 of a silicon oxide film is deposited on the entire surface of the semiconductor substrate 100 by the CVD using, for example, TEOS (tetraethoxysilane), and a contact hole 113 is formed in the interlayer insulating film 112 by the known photolithography technique and etching  
15 technique.

Then, for example, an aluminum alloy film is deposited on the entire surface of the semiconductor substrate 100 so as to fill the contact hole 113 by, for example, the sputtering, and the aluminum alloy film is patterned by the  
20 known photolithography technique and etching technique into a metal interconnect 114. Thereafter, a protection insulating film 115 of a multi-layer film including, for example, a silicon oxide film and a silicon nitride film is deposited on the metal interconnect 114 by, for example, plasma CVD. Thus,  
25 the semiconductor device of Embodiment 1 is completed.

The metal interconnect 114 may be formed from, instead of the aluminum alloy film, a multi-layer film including an aluminum alloy film and a titanium nitride film or tungsten film.

5 According to Embodiment 2, the second epitaxial silicide layer 111B of cobalt disilicide is formed in the surface portions of the n-type high concentration impurity layer 108 and the gate electrode 105. Therefore, the sheet resistance of the n-type high concentration impurity layer  
10 108 and the gate electrode 105 can be lowered to approximately  $5 \Omega / \square$ , which is much lower than the sheet resistance (of  $100 \Omega / \square$ ) obtained without forming the second epitaxial silicide layer 111B. In addition, the contact resistance can be also lowered, so that the performance of a  
15 semiconductor integrated circuit device including the MOSFET can be improved.

Furthermore, according to Embodiment 2, the metal film such as the cobalt film 110 is deposited after distributing the nonmetal element such as the oxygen atoms 109 in the  
20 regions in the vicinity of the surfaces of the n-type high concentration impurity layer 108 and the gate electrode 105, and thereafter, the first and second rapid thermal annealing are carried out so as to form the second epitaxial silicide layer 111B of cobalt disilicide in the surface portions of  
25 the n-type high concentration impurity layer 108 and the gate

electrode 105. Accordingly, the cobalt atoms and the silicon atoms are prevented from too rapidly reacting with each other, so that the agglomeration and the polycrystallization of the second epitaxial silicide layer 111B can be avoided and that  
5 a spike defect can be prevented from being caused in the second epitaxial silicide layer 111B. As a result, disconnection derived from the agglomeration or the polycrystallization of the epitaxial silicide layer can be prevented as well as junction leakage derived from a spike  
10 defect can be prevented.

Moreover, according to Embodiment 2, with the oxygen atoms 109 distributed in the regions in the vicinity of the surfaces of the n-type high concentration impurity layer 108 and the gate electrode 105, namely, with the oxygen atoms 109  
15 present at a low concentration between the n-type high concentration impurity layer 108 or the gate electrode 105 and the cobalt film 110, the first rapid thermal annealing is carried out. Therefore, the first rapid thermal annealing can be carried out at a low temperature of, for example,  
20 500°C.

Although the second epitaxial silicide layer 111B of cobalt disilicide is formed in the surface portions of both the n-type high concentration impurity layer 108 and the gate electrode 105 in Embodiment 2, the second epitaxial silicide  
25 layer 111B may be formed in the surface portion of either the



n-type high concentration impurity layer 108 or the gate electrode 105 instead.

Although the oxygen atoms are distributed as the nonmetal element in the regions in the vicinity of the surfaces of the n-type high concentration impurity layer 108 and the gate electrode 105 in Embodiment 2, nitrogen atoms or fluorine atoms may be distributed instead of the oxygen atoms.

Although the cobalt film 110 is deposited as the metal film so as to form the second epitaxial silicide layer 111B of cobalt disilicide in Embodiment 2, a metal film of another transition metal such as nickel and iron may be deposited instead of the cobalt film 110, so as to form an epitaxial silicide layer from the transition metal included in the metal film and silicon.

### EMBODIMENT 3

Another method for fabricating the semiconductor device of Embodiment 1 will now be described as Embodiment 3 of the invention with reference to FIGS. 5(a) through 5(c), 6(a) through 6(c), 7(a) and 7(b).

First, as is shown in FIG. 5(a), in the same manner as in Embodiment 2, a p-type well region 202 is formed by ion implanting a p-type impurity such as boron into a semiconductor substrate 200 of n-type silicon crystal, and then, a field insulating film 203 with a thickness of, for example, 400 nm is formed in a surface portion of the

semiconductor substrate 200 by the LOCOS. Subsequently, after a gate insulating film 204 of a silicon oxide film with a thickness of, for example, 5 through 10 nm is formed on the entire surface of the semiconductor substrate 200, a polysilicon film is deposited on the gate insulating film 204 by, for example, the CVD, and the polysilicon film is patterned into a gate electrode 205.

Next, with the gate electrode 205 used as a mask, an n-type impurity such as arsenic and phosphorus is ion implanted into the semiconductor substrate 200 at a low concentration, so as to form an n-type low concentration impurity layer 206 as is shown in FIG. 5(b).

Then, a silicon oxide film is deposited on the entire surface of the semiconductor substrate 200, and the silicon oxide film is subjected to the anisotropic etching, so as to form a sidewall 207 on the side face of the gate electrode 205 as is shown in FIG. 5(c). Thereafter, with the gate electrode 205 and the sidewall 207 used as masks, an n-type impurity such as arsenic and phosphorus is ion implanted into the semiconductor substrate 200 at a high concentration, so as to form an n-type high concentration impurity layer 208. Then, the semiconductor substrate 200 is subjected to annealing, thereby activating the n-type low concentration impurity layer 206 and the n-type high concentration impurity layer 208.

Then, as is shown in FIG. 6(a), a compound layer of a semiconductor element and a nonmetal film, such as a silicon oxide film 209, with a thickness of approximately 10 nm is formed on the entire surface of the semiconductor substrate 200.

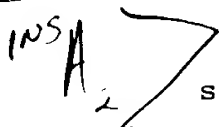
The silicon oxide film 209 may be formed by any of the following methods: In the first method, a solution with oxidizing power (such as a mixed solution of ammonia, hydrogen peroxide and pure water) is supplied onto the surface of the semiconductor substrate 200, thereby forming the so-called chemical oxide ( $\text{SiO}_2$ ) film; in the second method, the semiconductor substrate 200 is exposed to oxygen plasma, thereby forming a silicon oxide film with a thickness of approximately 10 nm; and in the third method, the semiconductor substrate 200 is heated to 750 through 900°C in an oxidizing atmosphere, thereby forming a thermally oxidized film with a thickness of approximately 10 nm.

Next, as is shown in FIG. 6(b), the silicon oxide film 209 is irradiated with a particle energy beam including a nonmetal element, such as an Ar ion beam, at low energy. In this manner, owing to recoil of the particle energy beam, oxygen atoms included in the silicon oxide film 209 are distributed in a direction along the substrate surface in regions in the vicinity of the surfaces of the n-type high concentration impurity layer 208 and the gate electrode 205,

so as to form an oxygen atom distributed region 210 as is shown in FIG. 6(c). In this case, the oxygen atoms included in the silicon oxide film 209 may be sputtered through the irradiation with the particle energy beam.

5 Also, the depth for distributing the oxygen atoms of the oxygen atom distributed region 210 is preferably 0.5 through 5 nm from the surface of the n-type high concentration impurity layer 208 or the gate electrode 205, and the concentration of the oxygen atoms in the oxygen atom  
10 distributed region 210 is preferably  $4 \times 10^{14} \text{ cm}^{-2}$  through  $4 \times 10^{15} \text{ cm}^{-2}$ . The reasons are the same as those described in Embodiment 2.

In the case where Ar ions are used for the irradiation of the particle energy beam, the peak of the distribution of  
15 the oxygen atoms in the oxygen atom distributed region 210 is at a depth of 1 nm from the surface of the silicon region when the acceleration energy of the Ar ions is 100 eV, and the peak of the distribution of the oxygen atoms is at a depth of 2 nm from the surface of the silicon region when the  
20 acceleration energy of the Ar ions is 300 eV.

INS A  Next, as is shown in FIG. 7(a), after removing the silicon oxide film 209, the sputtering is carried out in a sputtering system having a chamber kept at a degree of vacuum of  $1 \times 10^5$  through  $1 \times 10^7$  Pa, thereby depositing a metal  
25 film, such as a cobalt film 211, on the entire surface of the

semiconductor substrate 200. In this manner, similarly to Embodiment 2, cobalt atoms included in the cobalt film 211 are incorporated into the crystal lattice of silicon. Therefore, a nucleus of cobalt disilicide ( $\text{CoSi}_2$ ) is formed  
5 on the interface between the n-type high concentration impurity layer 208 and the cobalt film 210, and a nucleus of cobalt disilicide ( $\text{CoSi}_2$ ) is formed with respect to each crystal grain of the gate electrode 205.

Then, first rapid thermal annealing (RTA) is carried  
10 out for keeping the semiconductor substrate 200 at a temperature of  $500^\circ\text{C}$  for 10 seconds, so as to form a first epitaxial silicide layer 212A in surface portions of the n-type high concentration impurity layer 208 and the gate electrode 205.

15 Since the oxygen atom distributed region 210 is formed in the regions at the depth of 0.5 through 5 nm from the surface in the vicinity of the surfaces of the n-type high concentration impurity layer 208 and the gate electrode 205 in Embodiment 3, the cobalt atoms and the silicon atoms are  
20 not too rapidly reacted with each other. Therefore, the agglomeration or polycrystallization of the first epitaxial silicide layer 212A can be avoided.

Now, a measurement result of the concentration of the oxygen atoms in the oxygen atom distributed region 210 will  
25 be described.

FIG. 8 shows the result obtained by measuring the concentration of the oxygen atoms by low energy SIMS, in which the abscissa indicates the oxygen concentration (unit: number of atoms/cm<sup>2</sup>) and the ordinate indicates the degree of epitaxial growth. The degree of epitaxial growth can be expressed by intensity, and as the value of intensity is larger, the degree of epitaxial growth is larger. In this case, the ordinate indicates the peak intensity of CoSi<sub>2</sub> (400).

It is understood from the data shown in FIG. 8 at what concentration oxygen should be distributed in the vicinity of the surface of the semiconductor substrate 200 for forming the first epitaxial silicide layer 212A of cobalt disilicide (CoSi<sub>2</sub>). Also, it is understood from FIG. 8 that cobalt disilicide can be epitaxially grown practically without causing a problem of heat resistance when the value on the ordinate is larger than 100. Specifically, as far as the value on the ordinate is larger than 100, cobalt disilicide can attain heat resistance against a high temperature of approximately 800 °C, so as to avoid the agglomeration at a high temperature. The value on the ordinate is larger than 100 when the concentration of oxygen is  $4 \times 10^{14} \text{ cm}^{-2}$  through  $4 \times 10^{15} \text{ cm}^{-2}$ .

Accordingly, when the concentration of the oxygen atoms in the oxygen atom distributed region 210 is controlled to be

4 × 10<sup>14</sup> cm<sup>-2</sup> through 4 × 10<sup>15</sup> cm<sup>-2</sup>, the first epitaxial silicide layer **212A** can be satisfactorily grown without causing the agglomeration of cobalt disilicide (CoSi<sub>2</sub>).

In the first epitaxial silicide layer **212A**, all layers  
5 may be formed from cobalt disilicide (CoSi<sub>2</sub>), or the lowermost layer (closer to the silicon layer) may be formed from cobalt disilicide (CoSi<sub>2</sub>) with the uppermost layer (closer to the cobalt film **110**) formed from cobalt silicide (CoSi). In this manner, the agglomeration of the cobalt  
10 silicide layer can be prevented, resulting in reducing a leakage current.

Next, as is shown in FIG. 7(b), a portion of the cobalt film **211** not reacted in the first rapid thermal annealing is removed by using an etchant of, for example, a mixture of an  
15 ammonia solution and hydrogen peroxide or a mixed acid solution including hydrochloric acid. Thereafter, second rapid thermal annealing (RTA) is carried out for keeping the semiconductor substrate **200** at a temperature of 800°C for 10 seconds. Thus, the first epitaxial silicide layer **212A** is  
20 changed into a second epitaxial silicide layer **212B** in which all layers are formed from cobalt disilicide.

In the case where all the layers of the first epitaxial silicide layer **212A** are formed from cobalt disilicide, the second rapid thermal annealing can be omitted. In this case,  
25 the second epitaxial silicide layer **212B** mentioned in the

following description is read as the first epitaxial silicide layer 212A.

Thereafter, although not shown in the drawings, an interlayer insulating film, a contact hole, a metal  
5 interconnect and a protection insulating film are formed in the same manner as in Embodiment 2. Thus, the semiconductor device of Embodiment 1 is completed.

According to Embodiment 3, the second epitaxial silicide layer 212B of cobalt disilicide is formed in the  
10 surface portions of the n-type high concentration impurity layer 208 and the gate electrode 205. Therefore, the sheet resistance of the n-type high concentration impurity layer 208 and the gate electrode 205 can be lowered to approximately  $5 \Omega/\square$ , and the contact resistance can be also  
15 lowered. As a result, the performance of a semiconductor integrated circuit device including the MOSFET can be improved.

Also, according to Embodiment 3, the particle energy beam is irradiated after depositing the silicon oxide film  
20 209 on the semiconductor substrate 200. Therefore, the oxygen atoms 210 included in the silicon oxide film 209 can be definitely distributed in the regions in the vicinity of the surfaces of the n-type high concentration impurity layer 208 and the gate electrode 205.

25 Furthermore, the metal film such as the cobalt film 211



is deposited after the nonmetal element such as the oxygen atoms 210 is distributed in the regions in the vicinity of the surfaces of the n-type high concentration impurity layer 208 and the gate electrode 205, and then, the first and  
5 second rapid thermal annealing are carried out so as to form the second epitaxial silicide layer 212B of cobalt disilicide in the surface portions of the n-type high concentration impurity layer 208 and the gate electrode 205. Therefore, the cobalt atoms and the silicon atoms are prevented from too  
10 rapidly reacting with each other. As a result, the agglomeration or polycrystallization of the second epitaxial silicide layer 212B can be avoided as well as a spike defect can be prevented from being caused in the second epitaxial silicide layer 212B. In this manner, the disconnection  
15 derived from the agglomeration or polycrystallization of the epitaxial silicide layer can be prevented as well as the junction leakage derived from a spike defect can be prevented.

Moreover, according to Embodiment 3, the first rapid thermal annealing is carried out with the oxygen atoms 210  
20 distributed in the regions in the vicinity of the surfaces of the n-type high concentration impurity layer 208 and the gate electrode 205. Therefore, the first rapid thermal annealing can be carried out at a low temperature such as 500°C.

Although the second epitaxial silicide layer 212B of  
25 cobalt disilicide is formed in the surface portions of both

the n-type high concentration impurity layer 208 and the gate electrode 205 in Embodiment 3, the second epitaxial silicide layer 212B may be formed in the surface portion of either the n-type high concentration impurity layer 208 or the gate electrode 205 instead.

Although the silicon oxide film 209 is formed on the semiconductor substrate 200 in Embodiment 3, a silicon nitride film or a silicon fluoride film may be deposited instead, so that nitrogen atoms or fluorine atoms can be distributed in the regions in the vicinity of the surfaces of the n-type high concentration impurity layer 208 and the gate electrode 205.

Although the cobalt film 211 is deposited as the metal film so as to form the second epitaxial silicide layer 212B of cobalt disilicide in Embodiment 3, a metal film of another transition metal such as nickel and iron may be deposited instead of the cobalt film 211, so as to form an epitaxial silicide layer from the transition metal included in the metal film and silicon.

#### 20 MODIFICATION OF EMBODIMENT 3

In Embodiment 3, the silicon oxide film 209 is removed after distributing the oxygen atoms 210 in the regions in the vicinity of the surfaces of the n-type high concentration impurity layer 208 and the gate electrode 205 by irradiating the silicon oxide film 209 with the particle energy beam

including a nonmetal element such as the Ar ions. In contrast, in a modification of Embodiment 3, the mass and the energy of the particles included the particle energy beam, such as the Ar ions, are controlled, so that the silicon oxide film 209 can be removed through the irradiation with the particle energy beam in distributing the oxygen atoms 210 in the regions in the vicinity of the surfaces of the n-type high concentration impurity layer 208 and the gate electrode 205. In this manner, the procedure for removing the silicon oxide film 209 can be omitted.

#### Industrial Applicability

According to first or second method for fabricating a semiconductor device of this invention, rapid thermal annealing is carried out with a nonmetal element distributed in a region in the vicinity of the surface of a semiconductor layer, so as to cause a reaction between an element included in the semiconductor layer and a metal included in a metal film. Therefore, the metal included in the metal film and the element included in the semiconductor layer can be prevented from too rapidly reacting with each other. Accordingly, polycrystallization of an epitaxially grown semiconductor-metal compound layer can be avoided.

As a result, according to the invention, an epitaxially grown semiconductor-metal compound layer free from

agglomeration and a spike defect can be stably formed at a degree of vacuum generally employed in the semiconductor mass production process and at a low temperature.

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